Fundamentals of Stealth Design

Battle-proven Lockheed F-117 Stealth Fighter and the YF-22 Advanced Tactical Fighter prototype.

Design for low observability and specifically for low radar cross section began almost as soon as radar was invented. The predominantly wooden de Havilland Mosquito was one of the first aircraft to be designed with this capability in mind. Against World War II radar systems, that approach was fairly successful, but it would not be appropriate today.

First, wood and, by extension, composite materials are not transparent to radar, although they may be less reflective than metal; and second, the degree to which they are transparent merely amplifies the components which are normally hidden by the outer skin. These include engines, fuel, avionics packages, electrical and hydraulic circuits, and people.

In the late 1950s, radar-absorbing materials were incorporated into the design of otherwise conventionally designed aircraft. These materials had two purposes: to reduce the aircraft cross section against specl 'fic threats and to isolate multiple antennas on aircraft to prevent cross-talk. The Lockheed U-2 reconnaissance airplane is an example in this category.

By the 1960s, sufficient analytical knowledge had disseminated into the design community that the gross effects of different shapes and components could be assessed. lt was quickly realized that a flat plate at right angles to an impinging radar wave has a very large radar signal, and a cavity, similarly located, also has a large return. Thus ' she inlet and exhaust systems of a jet aircraft would be expected to be dominant contributors to radar cross section in the nose-on and tall-on viewing directions, and the vertical tail dominates the side-on signature.

Airplanes could now be designed with appropriate shaping and materials to reduce their radar cross sections, but as good numerical design procedures were not available, it was unlikely that a completely balanced design would result. In other words, there was always likely to be a component which dominated the return in a particular direction. This was the era of the Lockheed SR-71 Blackbird.

Ten years later, numerical methods were developed which allowed a quantitative assessment of contributions from different parts of a body. It was thus possible to design an aircraft with a balanced radar cross section and to minimize the return from dominant scatterers. This approach led to the design of the Lockheed F- 117A and Northrop B-2 stealth aircraft.

Over the past 15 years there has been continuous improvement in both analytical and experimental methods, particularly with respect to integration of shaping and materials. At the same time, the counter-stealth faction is developing an increasing understanding of its requirements, forcing the stealth community into another round of improvements. The message is, that with all the dramatic improvements of the last tw6 decades, there is little evidence of leveling-off in capability. This article, consequently, must be seen only as a snapshot in time.

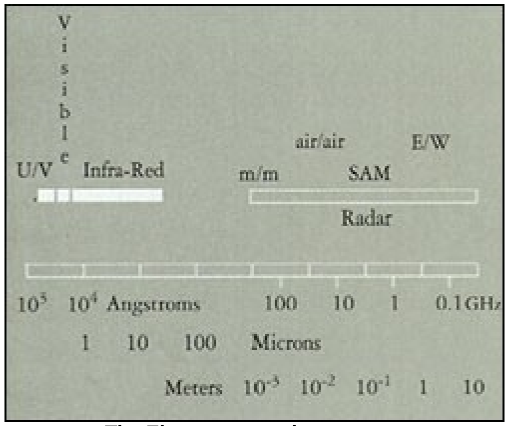
Radar Cross Section Fundamentals

There are two basic approaches to passive radar cross section reduction: shaping to minimize backscatter and coating for energy absorption and cancellation. Both of these approaches have to be used coherently in aircraft design to achieve the required lowobservable levels over the appropriate frequency range in the electromagnetic spectrum (see Figure). Shaping will be discussed first.

In a rare formation flight together, the Lockheed SR-71 and a Lockheed U-2 fly above the Mojave Desert in Southern California

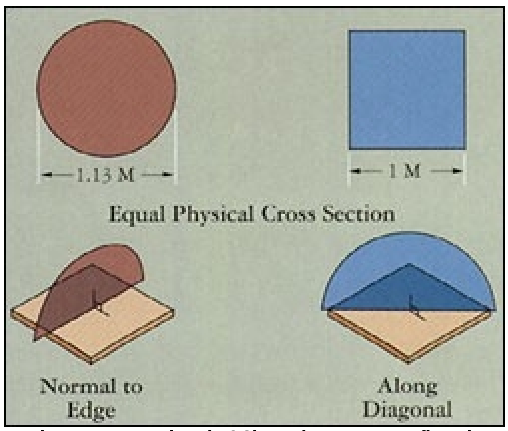
There is a tremendous advantage to positioning surfaces so that the radar wave strikes them at close to tangential angles and far from right angles to edges, as will now be illustrated. To a first approximation, when the diameter of a sphere is significantly larger than the radar wavelength, its radar cross section is equal to its geometric frontal area. In the example shown in two accompanying figures, the return from a one- square-meter sphere is compared to that from a one-meter-square plate at different look angles. One case to consider is a rotat'on of the plate from with the radar beam at right angles to a pair of edges. The other is with the radar beam at 45 degrees to the edges. The frequency is selected so that the wavelength is about i/io of the length of the plate, in this case very typical of acquisition radars on surface-to-alr missile systems.

At normal incidence, the flat plate acts like a mirror, and its returns 30 decibels (dB) above or 1000 times the return from the sphere. If we now rotate the plate about one edge so that the edge is always normal to the incoming wave, we find that the crosssection drops by a factor of 1000, equal to that of the sphere, when the look angle reaches 3o degrees off normal to the plate. As the angle is increased, the locus of maxima falls by about another factor Of 50, for a total change Of 50,000 from the normal look angle.

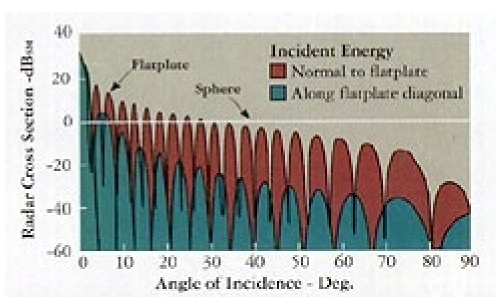


The Electro-magnetic spectrum

Now if we go back to the normal lncl idence case and rotate the plate about a diagonal relative to the incoming wave, we see a remarkable difference. In this case, the cross section drops bY 3o dB when the plate is only 8 degrees off normal, and drops another 4o dB by the time the plate is at a shallow angle to the incoming radar beam. This is a total change in radar cross section of io million!

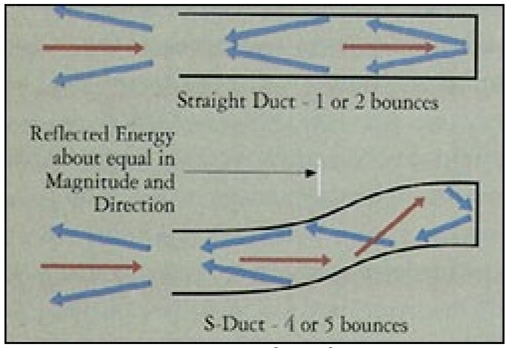


Radar cross section (RCS) - sphere versus flat plate



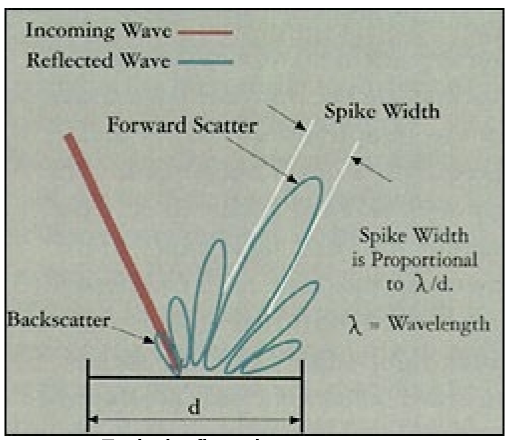
Radar cross section (RCS) - square plates

From this, it would seem that it is fairly easy to decrease the radar cross section substantially by merely avoiding obviously high-return shapes and attitude angles. However, we have not yet looked at multiple-reflection cases, which change the situation considerably. lt is fairly obvious that energy aimed into a long, narrow, closed cavity which is a perfect reflector internally will bounce back in the general direction of its source. Furthermore, the shape of the cavity downstream of the entrance clearly does not influence this conclusion.



Energy return from ducts

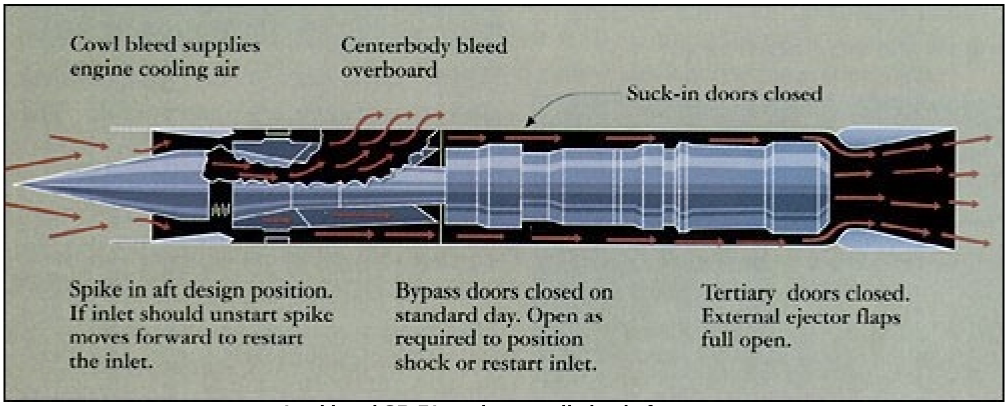
However, the energy reflected from a straight duct will be reflected in one or two bounces, while that from a curved duct will require four or five bounces (see Figure). It can be imagined that with a little skill, the number of bounces can be increased significantly without sacrificing aerodymanic performance. For example, a cavity might be designed with a high-cross-sectional aspect ratio to maximize the length-to-height ratio. If we can attenuate the signal to some extent with each bounce, then clearly there is a significant advantage to a multi-bounce design. The SR-71 inlet follows these design practices (see Figure).



Typical reflected wave structure

However, there is a little more to the story than just the so-called raytracing approach. When energy strikes a plate that is smooth compared to wavelength, it does not reflect totally in the optical approximation sense, i.e., the energy is not confined to a reflected wave at a complementary angle to the incoming wave. The radiated energy in fact takes a pattern like that shown as a typical reflected wave structure. The width of the main forward scattered spike is proportional to the ratio of the wavelength to the dimension of the reradlating surface, as are the magnitudes of the secondary and tertiary spikes. The classical optical approximation applies when this ratio approaches zero. Thus, the backscatter -the energy radiated directly back to the transmitter -increases as the wavelength goes up, or the frequency decreases.

When designing a cavity for minimum return, it is important to balance the forward scatter associated with ray tracing with the backscatter from interactions with the first surfaces. Clearly, an accurate calculation of the total energy returned to the transmitter is very complicated, and generally has to be done on a supercomputer using finite difference or moment method techniques.

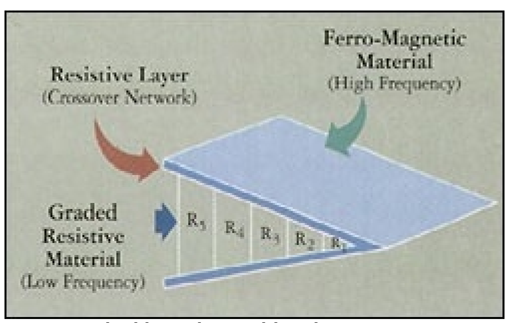


Lockheed SR-71 engine nacelle basic features

Coatings and Absorbers

It is fairly clear that although surface alignment is very important for external surfaces and inlet and exhaust edges, the return from the inside of a cavity is heavily dependent on attenuating materials. It is noted that the radar-frequency range of interest covers between two and three orders of magnitude. Permeability and dielectric constant are two properties that are closely associated with the electivity of an attentuating material.

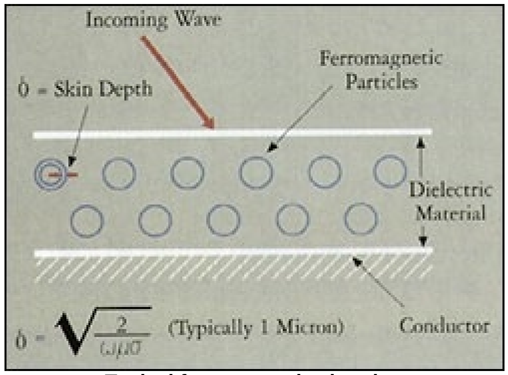
They both vary considerably with frequency in different ways for different materials. Also, for a coating to be effective, it should have a thickness that is close to a quarter wavelength at the frequency of interest. The reason for the importance of the quarter-wavelength dimension is illustrated. A typical ferromagnetic absorber will be made of a high dielectric material, in order to keep the thickness small, containing ferromagnetic particles, shown as solid spheres for simplicity.



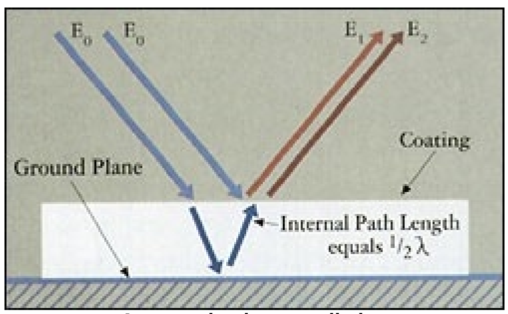
Typical low-observable edge treatment

The dielectric material slows the wave down, and the ferromagnetic particles absorb the energy. These effects by themselves, however, are insufficlent to reduce the scattered energy to the required levels. We must now invoke cancellation -a phenomenon that is illustrated. Incoming energy, E0, generally penetrates into the coating and most of it is absorbed. Some of the energy will reflect from the ground plane and, after further absorption, a small part, E,, escapes, having travelled along an internal path of half a wavelength.

The remaining energy, however, reflects off the first surface of the material as E1. The dependence of path length on angle of incidence is mitigated by having a high index of refraction, which keeps the refracted ray close to the normal. Fortunately, this is consistent with a high dielectric constant and a thin material. It will be seen that, not only must the coating be approximately a quarter-wavelength thick, but the escaping energy which has passed through the coating must be equal in amplitude to that which bounces off the first surface. This will ensure total cancellation of the returning wave, an ideal situation that is, of course, difficult to achieve.



Typical ferromagnetic absorber



Attentuation by cancellation

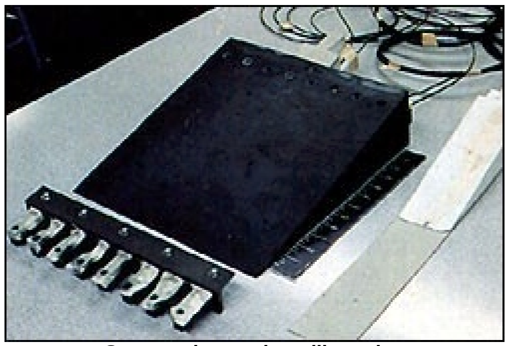
The key dimension of a quarter wavelength can vary in practice from millimeter to one meter. Although the coating designer will frequently try to use materials whose dielectric constant varies in a way that maintains a constant wavelength independent of frequency, the reality is that a number of different coatings and absorbers are needed to cover the required band'dth. An illustration of this is shown for a typical edge. Here we see a low frequency absorber that might be made of glass fiber hex-cell material. Its resistance is graded from front to back so that the edge is initially electromagnetically soft and gradually becomes more attenuating as the wave passes through. This approach is particularly taken when, for practical reasons, the edge cannot be as deep as a quarter wavelength. The inner absorber is covered by a high-frequency ferromagnetic coating, which completes the frequency coverage.

High Temperature Coatings

Reduction of radar cross section of nozzles Is also very important, and is complicated by high material temperatures. The electromagnetic design requirements for coatings are not different from those for low temperatures, and structural integrity is a much bigger issue.

The approach taken at Lockheed is to use ceramic materials analogously to the low-temperature materials addressed earlier. As shown, the ceramics may be either lightweight, parasitic

sheets mounted on conventional nozzle structures or heavier structural materials forming cantilevered edges. In both cases, the structural design issues are thermal expansion, material melting points, and edge brittleness.



Structural ceramic trailing edge

Jet Wakes

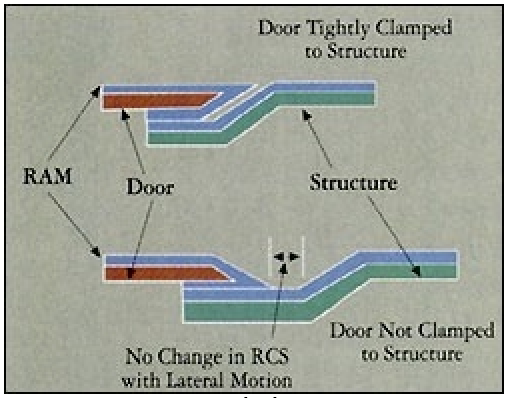
The driver determining radar return from a jet wake is the ionization present. Return from resistive particles, such as carbon, is seldom a significant factor. It is important in calculating the return from an ionized wake to use nonequilibrium mathematics, particularly for medium- and high-altitude cases. The very strong ion-density dependency on maximum gas temperature quickly leads to the conclusion that the radar return from the jet wake of an engine running in dry power is insignificant, while that from an afterburning wake could be dominant.

Structual ceramic trailing edge

Component Design

When the basic aircraft signature is reduced to a very low level, detail design becomes very important. Access panel and door edges, for example, have the potential to be major contributors to radar cross section unless measures are taken to suppress them. Based on the discussion of simple flat plates, it is clear that it is generally unsatisfactory to have a door edge at right angles to the direction of flight. This would result in a noticeable signal in a nose-on aspect. Thus, conventional rectangular doors and access panels are unacceptable. The solution is not only to sweep the panel edges, but to align those edges with other major edges on the aircraft. On the F- 117A, all panel edges are aligned with the trailing edge of the wing, so that their signatures are contained inside the basic wing signature. Even at that, it is important to minlmlze the signature of the edges. This is done by local radar-absorbing material coating and special shaping to minimize the effects of local cavities and of lateral motion of doors under load.

The pilot's head, complete with helmet, is a major source of radar return. It is augmented by the bounce-path returns associated with internal bulkheads and frame members. The solution is to design the cockpit so that its external shape conforms to good low radar cross section design rules, and then plate the glass with a film similar to that used for temperature control in commercial buildings. Here, the requirements are more stringent: it should pass at least 85% of the visible energy and reflect essentially all of the radar energy. At the same time, one would prefer not to have noticeable instrument-panel reflection during night flying.



Panel edges

On an unstable, fly-by-wire aircraft, it is extremely important to have redundant sources of aerodynamic data. These must be very accurate with respect to flow direction, and they must operate ice-free at all times. Static and total pressure probes have been used, but they clearly represent compromises with stealth requirements. Several quite different techniques are in various stages of development.

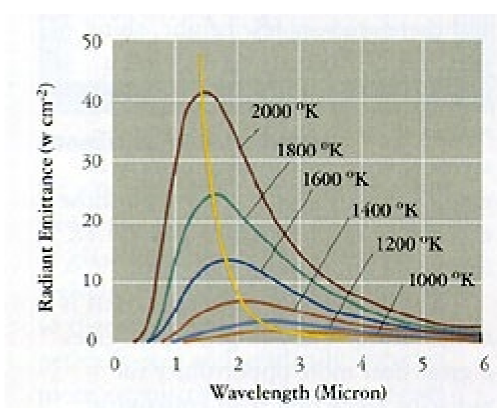
On-board antennas and radar systems are a major potential source of high radar visibility for two reasons. One is that it is obviously difficult to hide something that is designed to transmit with very high efficiency, so the so-called in-band radar cross section is liable to be significant. The other is that even if this problem is solved satisfactorily, the energy emitted by these systems can normally be readily detected. The work being done to reduce these signatures cannot be described here.

INFRARED RADIATION

There are two significant sources of infrared radiation from air-breathing propulsion systems: hot parts and jet wakes. The fundamental variables available for reducing radiation are temperature and emissivity, and the basic tool available is line-of-sight masking. Recently some progress has been made in directing energy, particularly for multiple bounce situations, but that subject wl ill not be discussed further here.

Emissivity can be a double-edged sword, particularly inside a duct. While a low emissivity surface will reduce the emitted energy, it will also enhance reflected energy that may be coming from a hotter internal region. Thus, a careful optimization must be made to determine the preferred emissivity pattern inside a jet engine exhaust pipe. This pattern must be played against the frequency range available to detectors, which typically covers a band from one to 12 microns. The short wavelengths are particularly effective at high temperatures, while the long wavelengths are most effective at typical ambient atmospheric temperatures. The required emissivity pattern as a function of both frequency and spatial dispersion having been determined, the next issue is how to make materials that fit the bill.

The first inclination of the infraredcoating designer is to throw some metal flakes into a transparent binder. Coming up with a transparent binder over the frequency range of interest is not easy, and the radar coating man probably won't like the effects of the metal particles on his favorite observable. The next move is usually to come up with a multi-layer material, where we use the same cancellation approach that was discussed earlier regarding radar-suppressant coatings. The dimensions now are in angstroms rather than millimeters. The big push at present is in moving from metal layers in the films to metal oxides for radar cross section compatibility. Getring the required performance as a function of frequency is not easy, and it is a significant feat to get down to an emissivity of o. i, particularly over a sustained frequency range. Thus, the biggest practical ratio of emissivities is liable to be one order of magnitude. We can all recognize that all of this discussion is meaningless if engines continue to deposit carbon (one of the highest emissivity materials known) on duct walls. For the infrared coating to be effective, it is not sufficient to have a very low particulars ratio in the engine exhaust, but to have one that is essentially zero. Carbon buildup on hot engine parts is a cumulative situation, and there are very few bright, shiny parts inside exhaust nozzles after a number of hours of operation. For this reason alone, it is likely that emissivity control will predominantly be employed on surfaces other than those exposed to engine exhaust gases, i.e., inlets and aircraft external parts.



Infrared radiant energy

The other variable available to us is temperature. This, in principle, gives a great deal more opportunity for radiation reduction than emissivity, because of the large exponential dependence. The general equation for emitted radiation is that it varies with the product of emissivity and temperature to the fourth power. However, this is a great simplification, because it does not account for the frequency shift of radiation with temperature. As illustrated, in the frequency range at which most simple detectors work, one to five microns, and at typical hot-metal temperatures, the exponential dependency will be typically near eight rather than four, and so at a particular frequency corresponding to a specific detector, the radiation will be proportional to the product of the emissivity and temperature to the eighth power. It is fairly clear that a small reduction in temperature can have a much greater effect than any reasonably anticipated reduction in emissivity.

The third approach is masking. This is clearly much easier to do when the majority of the power is taken off by the turbine, as in a propjet or helicopter application, than when the jet provides the basic propulsive force. The former community has been using this approach to infrared suppression for many years, but it is only recently that the jet-propulsion crowd has tackled this problem. The Lockheed F- 117 A and the Northrop B- 2 both use a similar approach of masking to prevent any hot parts being visible in the lower hemisphere.

In summary, infrared radiation should be tackled by a combination of temperature reduction and masking, although there is no point in doing these past the point where the hot parts are no longer the dominant terms in the radiation equation. The main body of the airplane has its own radiation, heavily dependent on speed and altitude, and the jet plume can be a most significant factor, particularly in afterburning operation. Strong cooperation between engine and air-frame manufacturers in the early stages of design is extremely important. The choice of engine bypass ratio, for example, should not be made solely on the basis of performance, but on a combination of that and survivability for maximum system effectiveness. The jet-wake radiation follows the same laws as the engine hot parts, a very strong dependency on temperature and a multiplicative factor of emissivity. Air has a very low emissivity, carbon particles have a high broadband emissivity, and water vapor emits in very specific bands. Infrared seekers have mixed feelings about water-vapor wavelengths, because, while they help in locating jet plumes, they hinder in terms of the general attenuation due to moisture content in the atmosphere. There is no reason, however, why smart seekers shouldn't be able to make an instant decision about whether conditions were favorable for using water-vapor bands for detection.

Summary

The low signatures achieved by modern special-purpose aircraft are due to a combination of shaping, material, material selection, and careful attention to detail design. Budgeting of component signatures across a wide range of frequencies and attitude angles is mandatory. Just as in a blackout, the game can be given away by one chink of light.

About the Author

ALAN BROWN *recently retired as Director of Engineering at Lockheed Corporate headquarters in Calabasas, California. Among his responsibilities was the development of concurrent engineering within the corporation. Prior to that, be was for several years director of low-observables technology at Lockheed Aeronautical Systems Company. From 1978 to 1982, be was the program manager and chief engineer for*

the F-117 Stealth Fighter and has been active in stealth programs since 1975.

He joined Lockheed in 1960, starting in the physics laboratory of the Research and Development Division of Lockheed Missiles & Space Company. He transferred to the Lockheed-California Company in Burbank, California, in 1966, working on propulsion installation on the supersonic transport (SST) and the FX and VSX aircraft (wbich became the F-5 and S-3A, respectively). Subsequently, he was engineering manager for the Lockheed group at Rolls-Royce on the L-1011 commercial transport program.

He began his aeronautical career with an engineering apprenticeship at Blackburn Aircraft in Englandfrom 1945 to 1950. He has masters degrees in aeronautical engineering from Cranfield Institute of Technology, England, and Stanford University, California, and is a Fellow of the Royal Aeronautical Society and an Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He received the AIAA Aircraft Design Award for 1990 for his contributions to the design of the F-117A, the world's first operational stealth fighter.